ELECTROCARDIOGRAM (ECG) MEASUREMENT 1

EXPERIMENT 1: ELECTROCARDIOGRAM (ECG) MEASUREMENT

1.0 PURPOSE OF THE EXPERIMENT

This module will help students understand the electrical activity that occurs during the heart's pumping process. The waveform created by this periodically changing potential is called an electrocardiogram (ECG). The module incorporates the concepts of Wilson network design and isolation circuit design and can be used to measure six different ECG signals.

1.1 PHYSIOLOGICAL PRINCIPLES

The human heart is composed of cardiac muscles (myocardium). When an action potential occurs, the heart muscles contract. This pumps blood throughout the body. The current generated by this action potential spreads from the heart throughout the body. Different current distributions are encountered in different parts of the body. Therefore, this signal can be measured with surface electrodes attached to the body. The measured waveform is called an electrocardiogram (ECG). Different potential waveforms and amplitudes can be recorded from different electrodes. There are six standard electrodes, consisting of Lead I, Lead II, Lead III, aV_R, aV_L, and aV_F, based on the heart potential axis. The right foot is considered the potential ground because of the very small change in potential amplitude and its location far from the heart. The pumping action of the heart is not entirely controlled by the autonomic nervous system. The heart's impulse originates from specialized cells in the sinoatrial node, which act as a pacemaker. The rhythmic action potential from the sinoatrial node spreads throughout the atria, resulting in atrial contraction. Myocardial contraction of the atria pumps blood into the ventricles. The action potential is transmitted to all parts of the ventricles via the atrioventricular node, between the ventricles, atrium, and Purkinje fibers. This process results in ventricular contraction, and blood is pumped from the ventricles into the arteries.

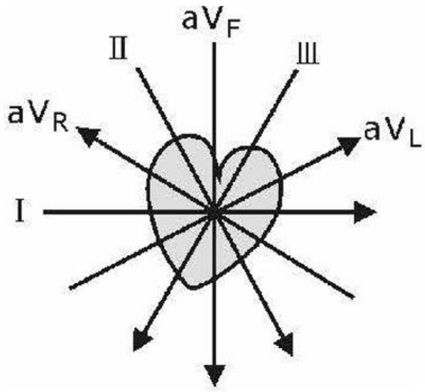


Figure 1.1 Heart potential axes corresponding to different ECG electrodes

As neural signals pass through the atria and ventricles, the current spreads into the cardiac tissue, causing the generation of a myocardial action potential. Portions of the action potential are reflected on the body surface. Consequently, if the electrodes are placed in the correct locations on the body, a potential waveform that varies over time during the heart's contraction and relaxation periods can be obtained. These waveforms are called ECGs. Figure 1.1 shows the potential axes used to measure signals from different ECG electrodes. The projection of the cardiac potential onto the front of the human body is called a cardiac vector. The two axes formed by the reflected vectors are 60 degrees apart. The directions of the four axes are independent of electrode positions. This concept was discovered by a Dutch physiologist named Willen Einthoven. The triangle shown in Figure 1.2 is called Einthoven's triangle.

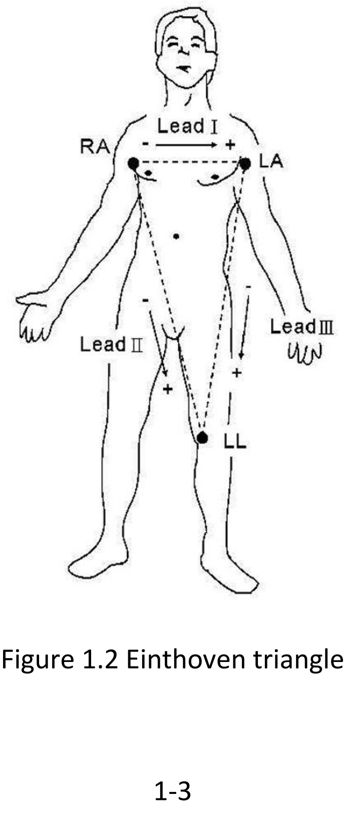


Figure 1.2 Einthoven triangle

Figure 1.3 is a normal ECG image consisting of a P wave, QRS wave, and T wave. The P wave is generated by the current generated by depolarization of atrial contraction, the QRS wave is generated by depolarization before ventricular contraction, and the T wave is generated by ventricular repolarization.

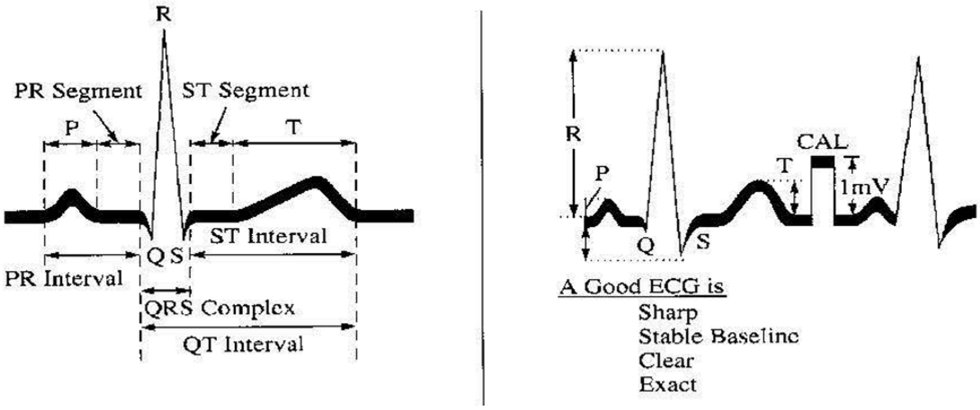


Figure 1.3 ECG wave duration and amplitude

Figure 1.4 shows bipolar measurements made with Lead I, Lead II, and Lead III in different vector directions. In unipolar measurements, the average of the two potentials at the hands and feet is referenced as signal ground (Figure 1.5). Unipolar measurements are divided into three types: augmented right arm voltage (aVR), augmented left arm voltage (aVL), and augmented foot voltage (aVF).

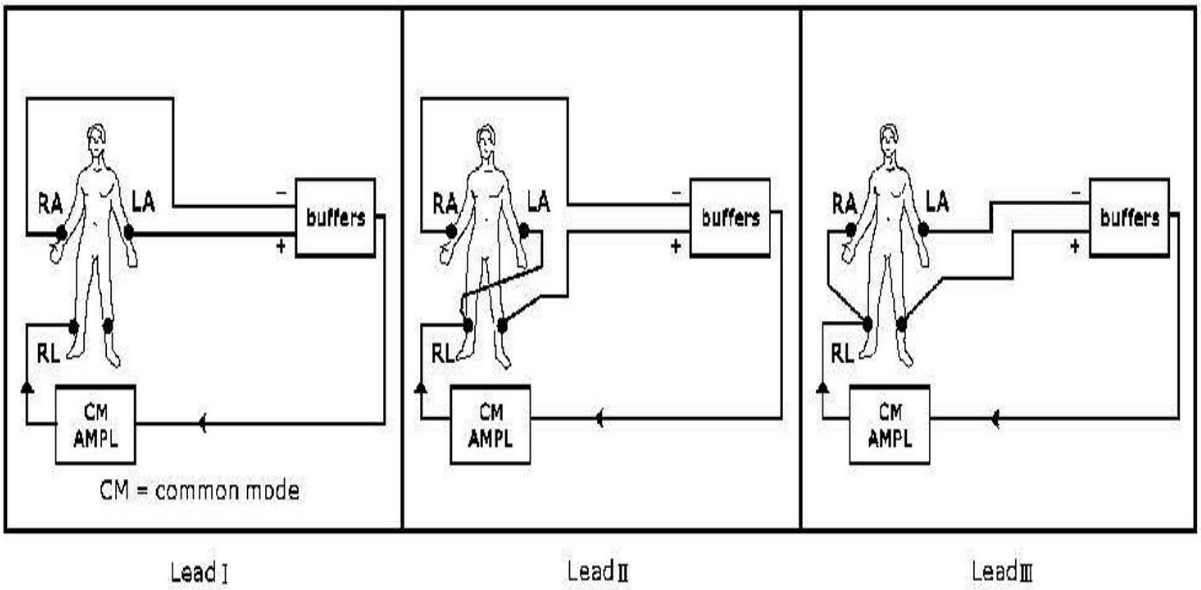


Figure 1.4 Bipolar measurements

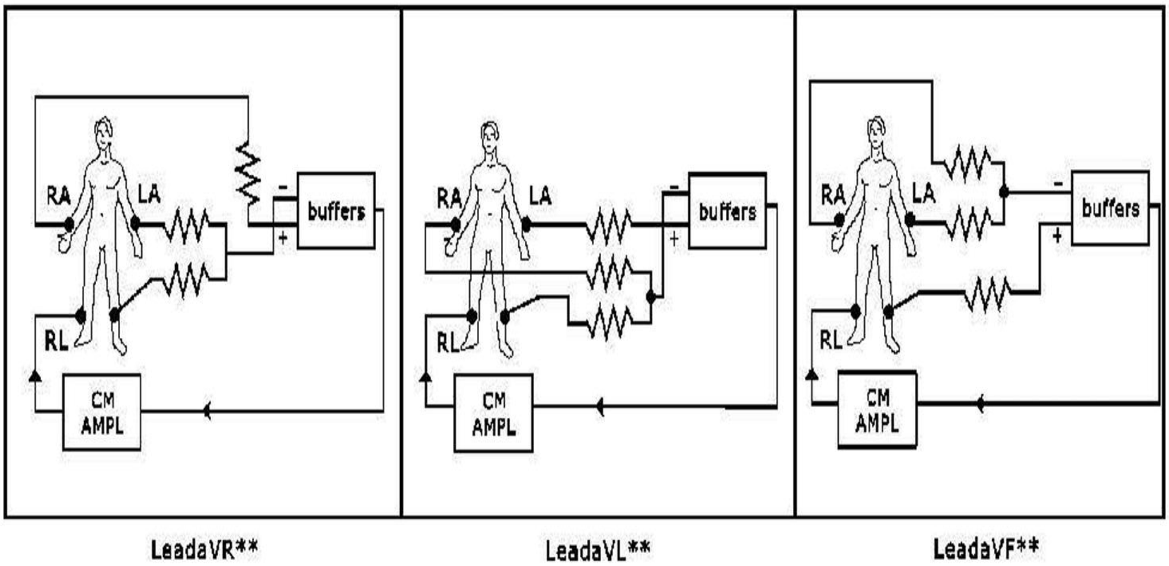


Figure 1.5 Unipolar measurements

1.2 CIRCUIT DESCRIPTIONS

1. ECG Measurement Circuit Block Diagram

As explained on the previous page, in measurements made with electrodes connected to the hands and feet, the right foot is always used as the reference ground. Six ECG signals, consisting of Lead I, Lead II, Lead III, aVR, aVL, and aVF, can be measured with combinations of connections between the right arm, left arm, and left foot. Considering hardware costs, a single-channel, multi-lead circuit is typically designed. The frequency range is generally 0.1-100Hz, and the maximum amplitude of a typical ECG signal is 1 mV. Furthermore, when designing a circuit for ECG measurement, an isolation system should be installed to prevent electric shock during use due to leakage from the power supply or measuring devices.

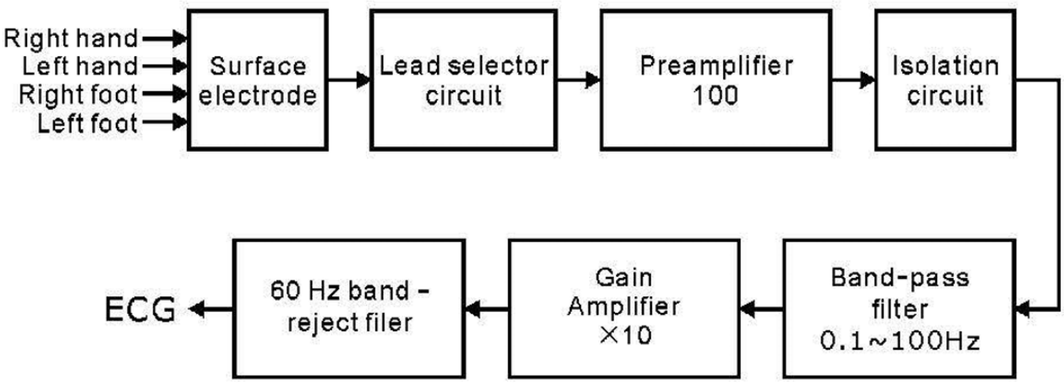


Figure 1.6 ECG Measurement Circuit Block Diagram

Figure 1.6 shows the block diagram of the ECG measurement circuit. In ECG measurement, surface electrodes (or clamp electrodes) placed on the hands and feet are used to detect a very weak, time-varying potential. The lead selector circuit includes a voltage-monitoring circuit to match the impedance between the electrode and the skin, increasing ECG detection sensitivity. The triangular selection network in the selector circuit is based on the various measurement modes shown in Figures 1.4 and 1.5. An instrumentation amplifier with a gain of 100 is used as a preamplifier to capture unipolar signals from the ECG vectors. The purpose of the isolation circuit here is to separate the signals from the power supply line and can be implemented optically or as a voltage converter. The bandwidth of the band-pass filter is 0.1-100 Hz, and the gain amplifier amplifies the signal from the filter by a factor of 10.

2. Lead Selector Circuit

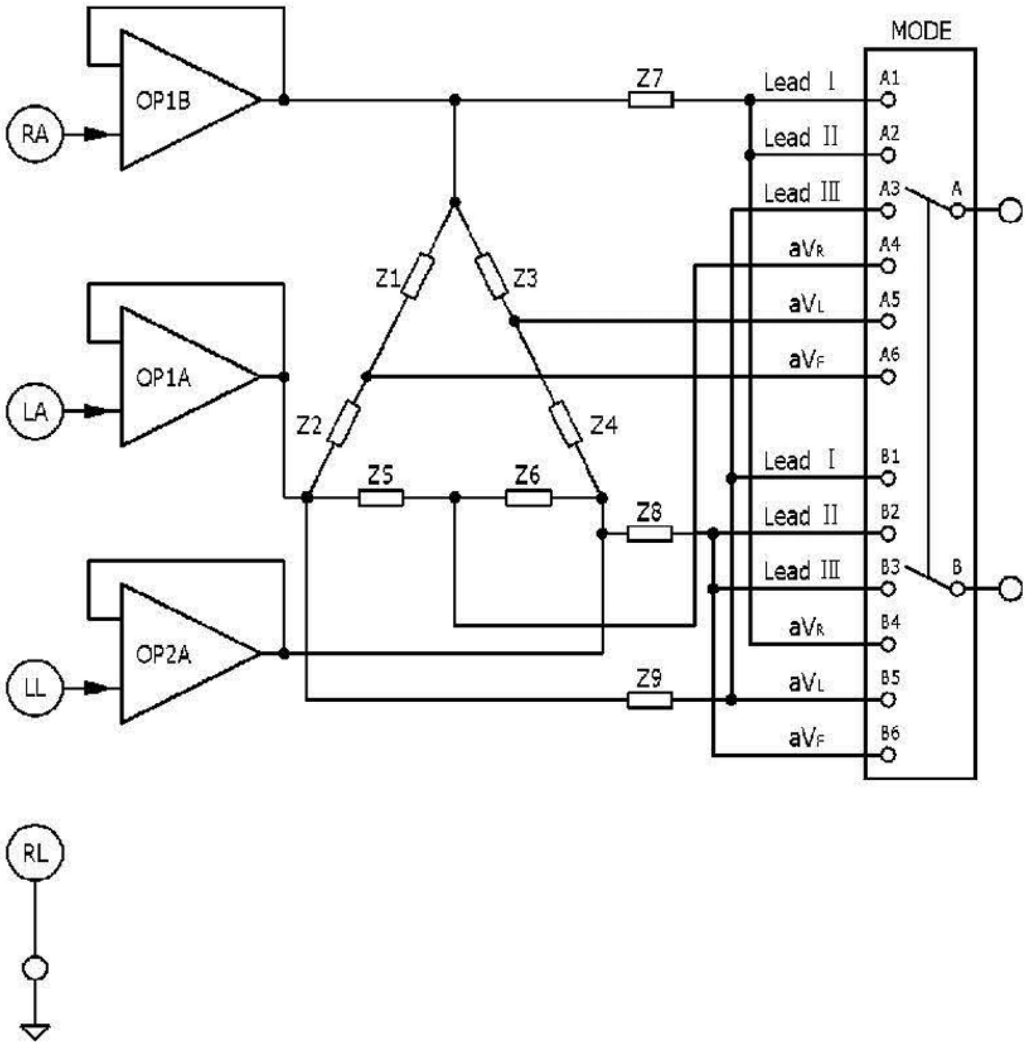


Figure 1.7 ECG Lead selection circuit

In the Lead Selector circuit, as shown in Figure 1.7, OP1 and OP2 are voltage-following amplifiers. OP1 and OP2 are selected from JFET operational amplifiers to increase the input resistance of the selector circuit. Resistors Z1-Z9 are the equivalent resistances used in the delta network circuit. In bipolar measurement, OP1B-Z7 and OP1A-Z9 are for Lead I, OP1B-Z7 and OP2A-Z8 are for Lead II, OP1A-Z9 and OP2A-Z8 are for Lead III, and RL is attached to the right leg as the ground reference. In unipolar measurement, OP1A-Z5 and OP2-Z6 and OP1B-Z7 are for aVR, OP1B-Z3 and OP2A-Z4 and OP1A-Z9 are for aVL, and OP1B-Z1 and OP1A-Z2 and OP2A-Z8 are for aVF.

3. Pre-amplifier Circuit

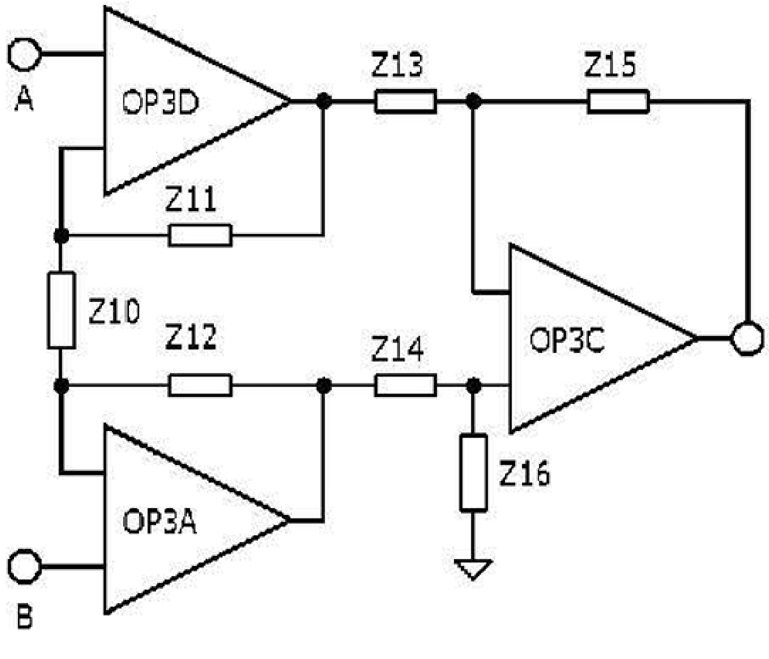


Figure 1.8 Pre-amplifier Circuit

Figure 1.8 shows the preamplifier circuit consisting of the OP3 instrumentation amplifier. When Z11=Z12, Z13=Z14 and Z15=Z16, the gain can be calculated as follows (Equation 1.1):

$$Av = \frac{Z_{15}}{Z_{13}}\left(1 + \frac{2Z_{11}}{Z_{10}}\right) \quad (1.1)$$

4. Isolation Circuit

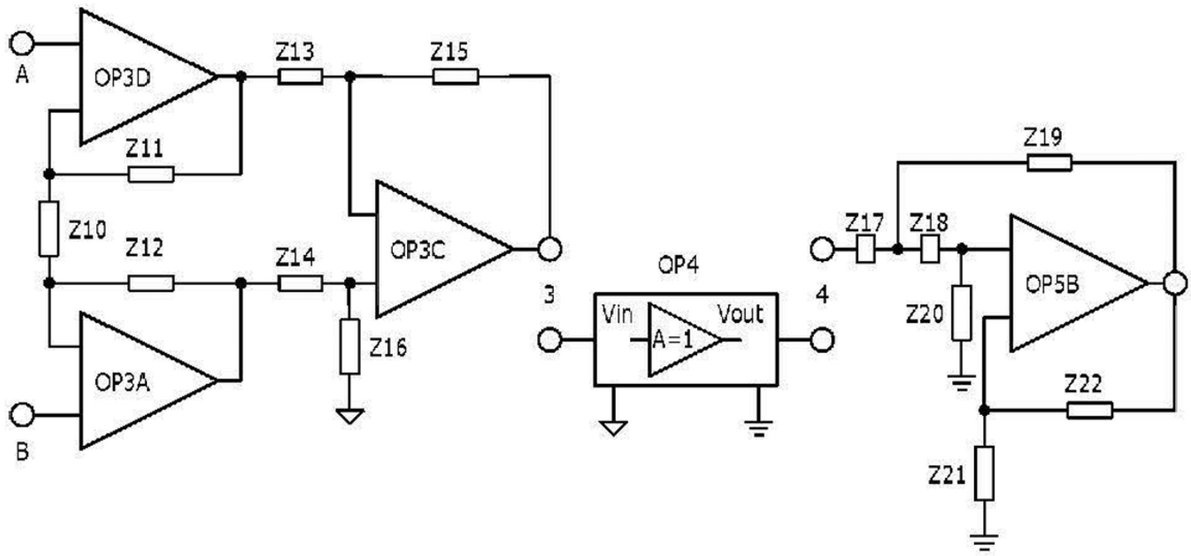
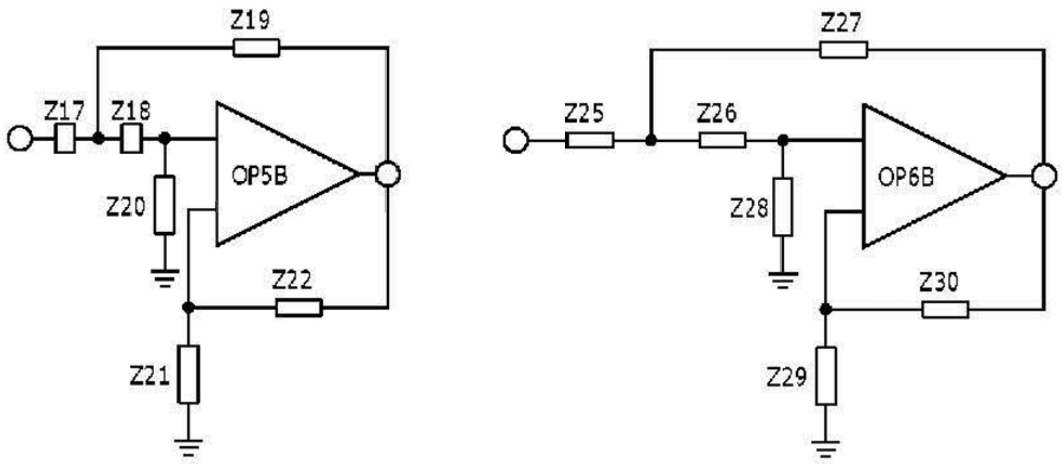


Figure 1.9 Isolation Circuit

As shown in Figure 1.9, the isolation circuit consists of OP4. Here, signal isolation is achieved through optical coupling.

5. Band-Pass Filter Circuit



(A) 2-order High-Pass Filter (B) 2-order Low-Pass Filter

Figure 1.10 Filter Circuits.

To reduce the DC component level of the ECG signal passing through the isolation circuit, OP5B was used to create an active 2-order high-pass filter as shown in Figure 1.10 A. The corner frequency (f_H) of the filter was set to 0.1 Hz, and this value can be calculated using Z17, Z18, Z19, and Z20, as shown in Equation 1.2.

$$f_H = \frac{1}{2\pi\sqrt{Z_{17}Z_{18}Z_{19}Z_{20}}} \quad (1.2)$$

The pole design is described in Equation 1.3,

$$\frac{(Z_{21}+Z_{22})}{Z_{21}} = 1.56 \quad (1.3)$$

Here, a bandwidth of 1 Hz was deliberately chosen to reduce transient fluctuations caused by the high-pass filter. OP6B was used to make an active 2-order low-pass filter, see Figure 1.10 B. The corner frequency (f_L) of the filter is set to 100 or 40 Hz, and this value can be calculated using Z25, Z26, Z27, and Z28, as shown in Equation 1.4.

$$f = \frac{1}{2\pi\sqrt{Z_{25}Z_{26}Z_{27}Z_{28}}} \quad (1.4)$$

The pole design is described in Equation 1.5,

$$\frac{(Z_{29}+Z_{30})}{Z_{29}} = 1.56 \quad (1.5)$$

When the corner frequency is set to 40Hz, the low-pass filter not only protects against 60Hz interference from the power supply, but also eliminates the need for a band-pass filter with a center frequency of 60Hz. Thus, this design can reduce phase distortion.

6. Gain Amplifier

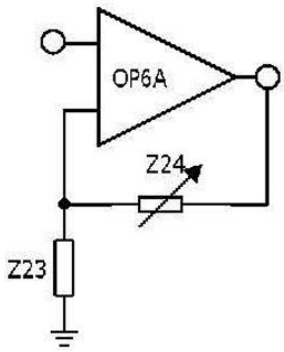


Figure 1.11 Non-inverting Amplifier

Figure 1.11 shows a non-inverting amplifier implemented using an OP6A. In the amplifier, Z24 is used for gain adjustment. The gain expression is explained in Equation 1.6:

$$A_V = \frac{(Z_{23} + Z_{24})}{Z_{23}} \qquad (1.6)$$

7. Band-Stop Filter Circuit

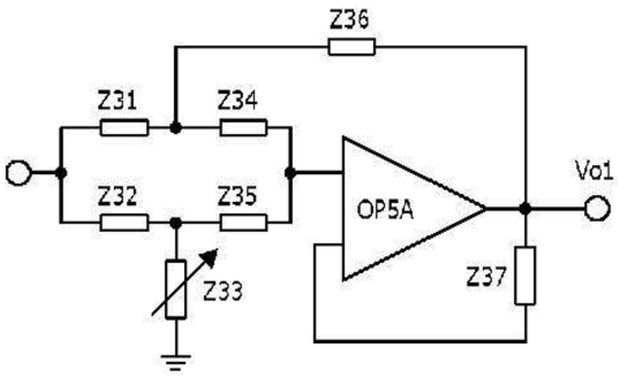


Figure 1.12 Band-Stop Filter

A double-T band-stop filter consisting of an RC circuit containing OP5A, Z31, Z32, Z33, Z34, Z35, and Z36 is shown in Figure 1.12. If Z31 = Z34, Z32 = Z35, Z33 = 0.5xR31, and Z36 = 2xZ32, the frequency to be blocked can be calculated as in Equation 1.7.

$$f = \frac{1}{2\pi\sqrt{Z_{31}Z_{32}Z_{34}Z_{35}}} \qquad (1.7)$$

1.3 REQUIRED EQUIPMENT

1. KL-71001 Main Controller
2. KL-73001 Experiment Module
3. Clamp-Tip Electrode
4. Digital Memory Oscilloscope (extra equipment)
5. ECG Simulator (extra equipment)
6. Cleaning Cloth (swab)
7. 10 mm Connector Plugs
8. Electrode Cables
9. HUB
10. D-Sub 9-9 Cable

1.4 HOW TO CONDUCT THE EXPERIMENT

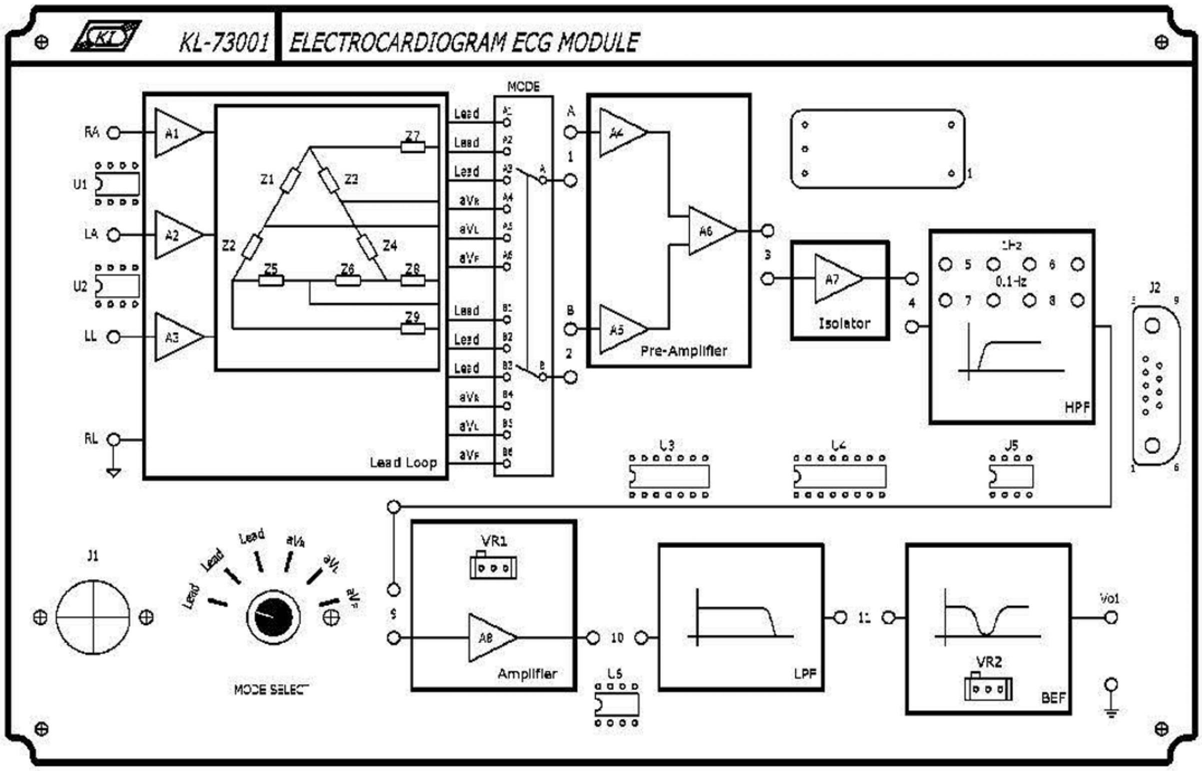


Figure 1.13 ECG Measurement Module

1. High-Pass Filter Characteristics Experiment

(1) Connect the J2 connector of the KL-73001 to the MODULE OUTPUT terminal of the KL-71001. A jumper plug is not required between any two circuit blocks.

(2) Connect the KL-71001's function generator output to terminal '4' of the KL-73001, and the KL-71001's GND terminal to the right ground terminal of the KL-73001. Set the function generator's sinusoidal frequency to its maximum value and its amplitude to 1 Vpp. Connect the inputs marked 5 and 6 of the KL-73001 with a jumper plug. Connect the function generator output to the CH1 channel of the oscilloscope and the HPF output terminal to the CH2 channel of the oscilloscope.

(3) Adjust the frequency to various values and record the output amplitude of the high-pass filter in the location shown in Table 1.1 in the Results section.

(4) Using the results in Table 1.1, plot the high-pass filter's characteristic curve in the location shown in Table 1.2 in the Results section.

(5) Remove the connection between terminals 5 and 6 and connect the inputs marked 7 and 8 together. Measurement at 0.1 Hz is not possible because the minimum frequency that can be generated by the function generator is 1 Hz. To measure at 0.1 Hz, a function generator capable of generating 0.1 Hz is required.

(6) Repeat steps 3 and 4, and record the results in the blanks shown in Tables 1.1 and 1.2 in the Results section.

2. Amplifier Experiment

(1) Connect the J2 connector of the KL-73001 to the MODULE OUTPUT input terminal of the KL-71001. There is no need for a connector between any two circuit blocks.

(2) Connect the function generator output of the KL-71001 to terminal 9 of the KL-73001, and the GND terminal of the KL-71001 to the right ground terminal of the KL-73001. Turn VR1 counterclockwise to its minimum value (a beep will be heard). Connect the function generator output to the CH1 channel of the oscilloscope, and the "Amplifier" output terminal to the CH2 channel of the oscilloscope.

(3) Set the function generator's sinusoidal frequency to 100Hz and its amplitude to 50mVpp. Record the amplifier output amplitude in the space shown in Table 1.3 in the Results section.

(4) Turn VR1 clockwise to its maximum value.

(5) If the amplifier output is in the saturation region, reduce the function generator output amplitude to prevent distortion.

3. Low-Pass Filter Characteristics Experiment

(1) Connect the J2 connector of the KL-73001 to the MODULE OUTPUT terminal of the KL-71001. There is no need for a connector between any two circuit blocks.

(2) Connect the function generator output of the KL-71001 to terminal '10' of the KL-73001, and the GND terminal of the KL-71001 to the right ground terminal of the KL-73001. Set the sinusoidal frequency of the function generator to its minimum value and its amplitude to 1 Vpp. Connect the function generator output to the CH1 channel of the oscilloscope, and the LPF output terminal to the CH2 channel of the oscilloscope.

(3) Adjust the frequency to various values and record the output amplitude of the low-pass filter in the location shown in Table 1.4 in the Results section.

(4) Based on the results in Table 1.4, plot the low-pass filter's characteristic curve in the location shown in Table 1.5 in the Results section.

4. Band-Stop Filter Characteristics Experiment

(1) Connect the J2 connector of the KL-73001 to the MODULE OUTPUT terminal of the KL-71001. There is no need for a connector between any two circuit blocks.

(2) Connect the KL-71001's function generator output to terminal '11' of the KL-73001, and the KL-71001's GND terminal to the right ground terminal of the KL-73001. Set the function generator's sinusoidal frequency to its minimum value and its amplitude to 1 Vpp. Connect the function generator output to the CH1 channel of the oscilloscope, and the BEF output terminal to the CH2 channel of the oscilloscope. Set VR2 to its midpoint.

(3) Adjust the frequency to various values and record the output amplitude of the band-stop filter in the location shown in Table 1.6 in the Results section.

(4) Using the results in Table 1.6, plot the characteristic curve of the band-stop filter in the location shown in Table 1.7 in the Results section.

(5) Using the results in Table 1.6, determine the value of VR2. The BEF output should be at its minimum when the input frequency is 60 Hz.

5. Simulated ECG Experiment (Extra Equipment)

**Refer to the standard ECG simulator output (the ECG simulator is an optional extra and must be purchased separately).

(1) Connect the J1 connector of the KL-73001 to the hub, and the J2 connector to the MODULE OUTPUT terminal of the KL-71001. Connect the terminals marked 1, 2, 3, 4, 5, 6, 9, 10, and 11 with the connectors. Connect the Vo1 output terminal to the oscilloscope.

(2) Use the INPUT SELECT button on the KL-71001 to select the KL-73001 module (see LCD display). The IN1, IN2, IN3, and IN5 LEDs on the KL-71001 front panel will light up. This means that the input signals must be connected to these input terminals.

(3) Connect the output of the ECG simulator to the hub. RA→IN1, LA→IN2, LL→IN3, and RL→IN5. Select 60 beats per minute or a different value.

(4) Set the MODE SELECT knob to Lead 1. Set VR1 on the amplifier to its midpoint. Adjust VR2 to minimize output waveform noise. Record the Vo1 output in the location shown in Table 1.8 in the Results section.

(5) Set the HPF frequency to 0.1 Hz and observe the effect on the output.

(6) Record the waveforms of the Lead 1, Lead 11, Lead 111, aVR, aVL, and aVF signals in the locations shown in Table 1.8 in the Results section.

(7) Set the oscilloscope input coupling to the AC coupling position.

6. Real ECG Experiment (ECG signals are recorded by a digital storage oscilloscope)

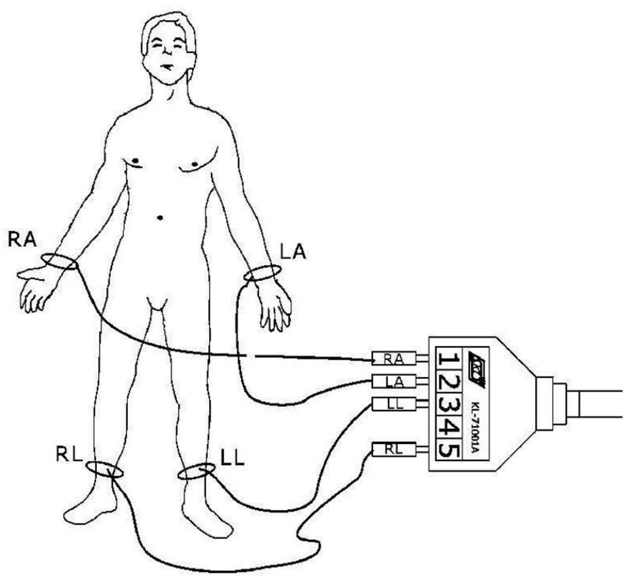
** Human ECG Experiment

(1) Connect the J1 connector of the KL-73001 to the hub and the J2 connector to the MODULE OUTPUT terminal of the KL-71001. Connect the terminals marked 1, 2, 3, 4, 5, 6, 9, 10, and 11 with the connectors. Connect the Vo1 output terminal to the oscilloscope.

(2) Use the KL-71001's 1 NPUT SELECT button (see LCD screen) to select the KL-73001 module. The IN1, IN2, IN3, and IN5 LEDs on the KL-71001's front panel will light up. This indicates that input signals should be connected to these input terminals.

(3) Wet the cuff-tipped electrodes and attach them to both arms and both ankles. You will generally need to clean the electrode attachment areas with a cleaning cloth.

(4) Referring to the image below, attach the electrodes to their cables and insert the electrode cables into the hub sockets: RA→IN1, LA→IN2, LL→IN3, and RL→IN5.



Clamp-Tip Attachment Locations and Hub Cable Connections.

(5) Record the waveforms of Lead 1, Lead 11, Lead 111, aVR, aVL, and aVF signals in the locations shown in Table 1.9 in the Results section.

7. Real ECG Experiment (ECG signals are recorded by a computer via the RS232 interface)

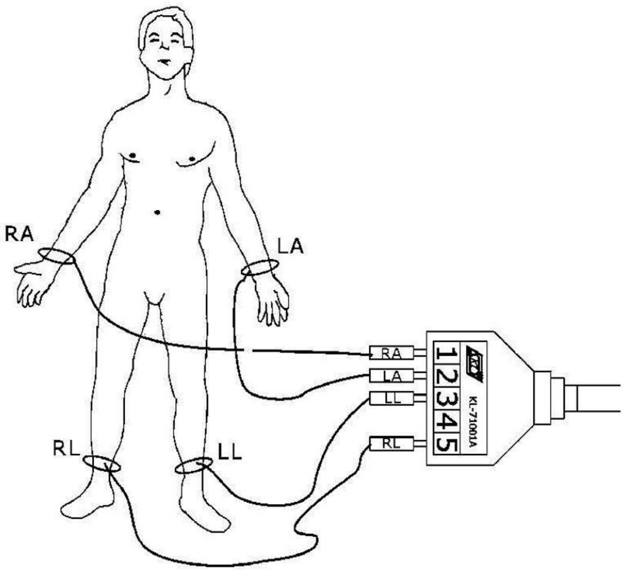
**** Human ECG Experiment**

(1) Connect the J1 connector of the KL-73001 to the hub and the J2 connector to the MODULE OUTPUT terminal of the KL-71001. Connect the terminals marked 1, 2, 3, 4, 5, 6, 9, 10, and 11 with the connectors. Connect the Vo1 output terminal to the oscilloscope.

(2) Use the INPUT SELECT button on the KL-71001 to select the KL-73001 module (see LCD screen). The IN1, IN2, IN3, and IN5 LEDs on the KL-71001 front panel will light up. This indicates that input signals should be connected to these input terminals.

(3) Wet the cuff-tipped electrodes and attach them to both arms and both ankles. You will generally need to clean the areas where the electrodes will be attached with a cleaning cloth.

(4) Referring to the image below, attach the electrodes to their cables and insert the electrode cables into the hub sockets: RA→IN1, LA→IN2, LL→IN3, and RL→IN5.

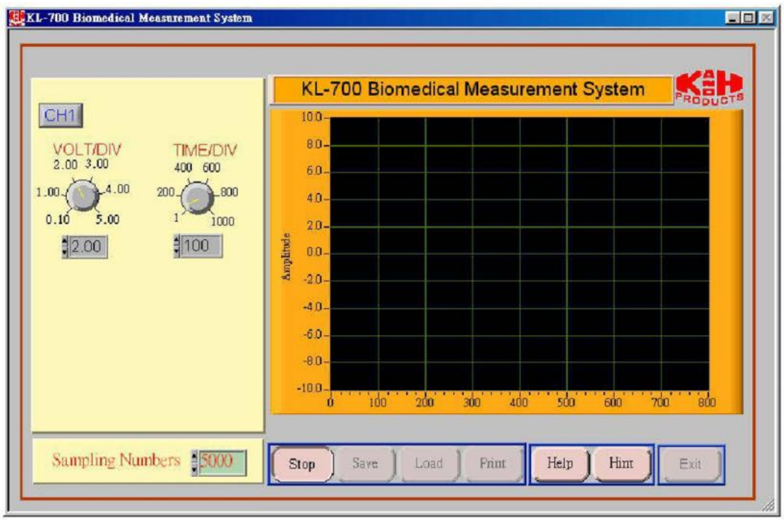


Clamp-Tip Attachment Locations and Hub Cable Connections.

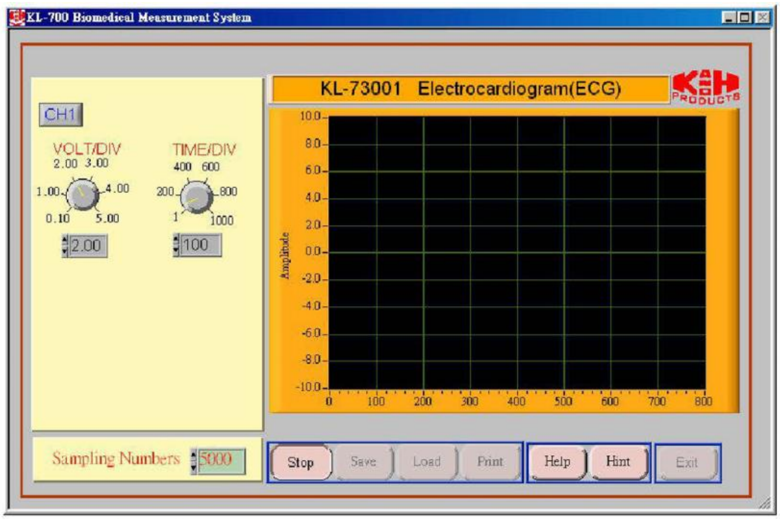
(5) Connect the 9-pin RS232 cable to the computer's communication port.

(6) Run the KL-700 Biomedical Measurement System software. See Section 0 for detailed installation and usage information.

(7) Once the system has loaded, the image below will appear.



(8) Press the 'Acqu' button to display the image below, the example shows the KL-73001 ECG Recording screen.



(9) Adjust the VOLT/DIV and TIME/DIV knobs appropriately to bring the signal waveforms to the center of the screen. Record the waveforms of Lead I, Lead II, Lead III, aVR, aVL, and aVF signals.

1.5 RESULTS

Table 1.1 High-Pass Filter Characteristics experiment.

(Connection plug at 5 and 6 – 1 Hz)

Frequency	1 KHz	500 Hz	100 Hz	10 Hz	5 Hz	4 Hz	3 Hz	2 Hz	1 Hz
HPF Output (Vpp)									

(Connection plug at 7 and 8 – 0.1 Hz)

Frequency	1 KHz	100 Hz	10 Hz	5 Hz	4 Hz	3 Hz	2 Hz	1 Hz	0.1 Hz
HPF Output (Vpp)									

Table 1.2 High-Pass Filter Characteristic Curve

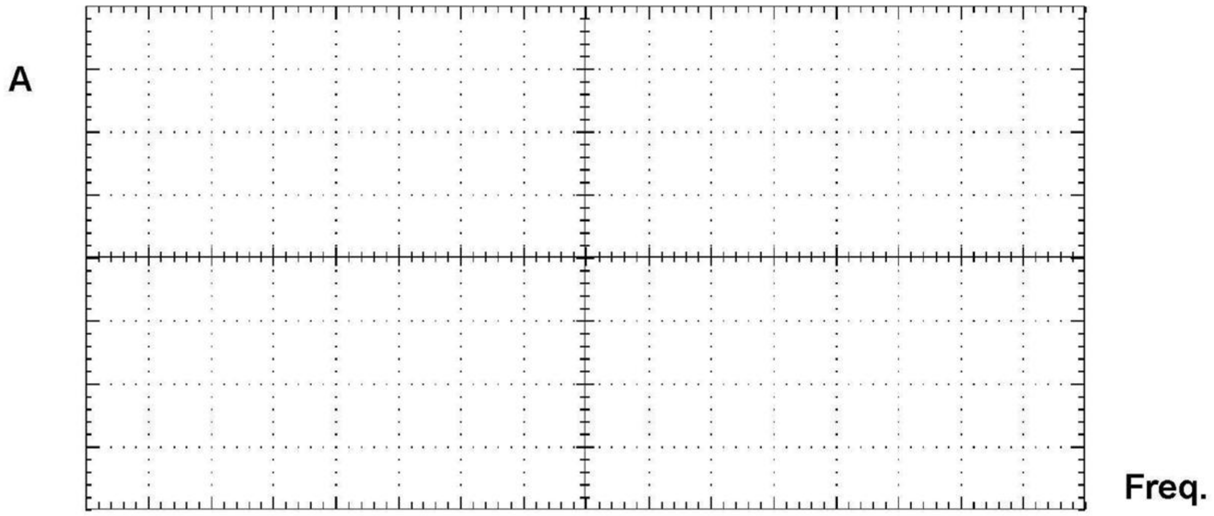


Table 1.3 Amplifier Experiment

Gain of Amplifier	**Amplifier output**
VR1 → Minimum	
VR2 → Maximum	

Table 1.4 Low-Pass Filter Characteristics experiment

Frequency	1 Hz	2 Hz	3 Hz	50 Hz	60 Hz	80 Hz	90 Hz	100 Hz	200 Hz
LPF Output (Vpp)									

Table 1.5 Low Pass Filter Characteristic Curve

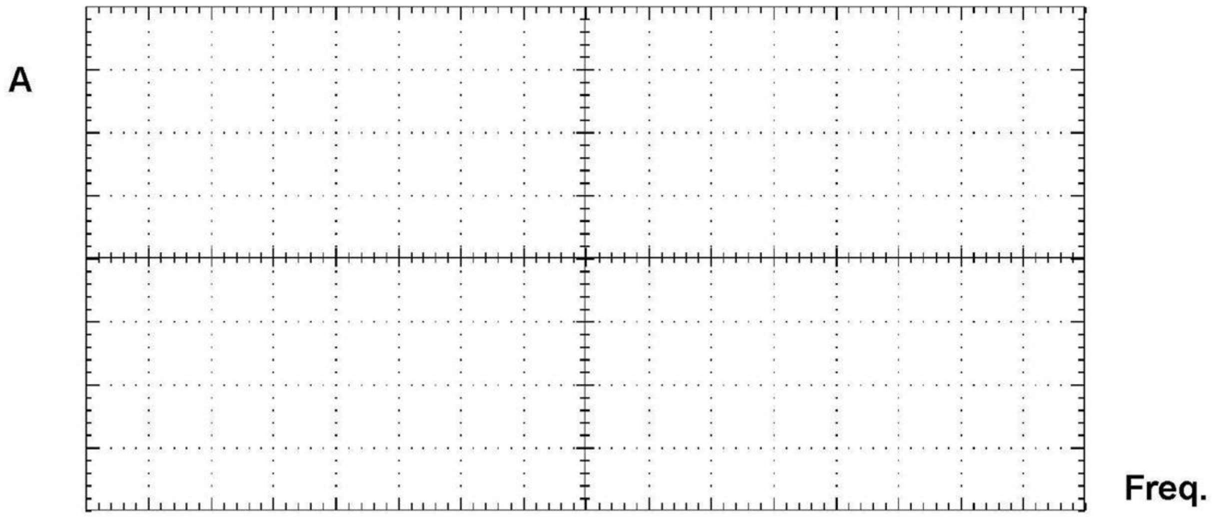


Table 1.6 Band-Stop Filter Characteristics experiment

Frequency	1 Hz	10 Hz	20 Hz	30 Hz	50 Hz	60 Hz	100 Hz	500 Hz	1 KHz
BEF Output (Vpp)									

Table 1.7 Band-Stop Filter Characteristic Curve

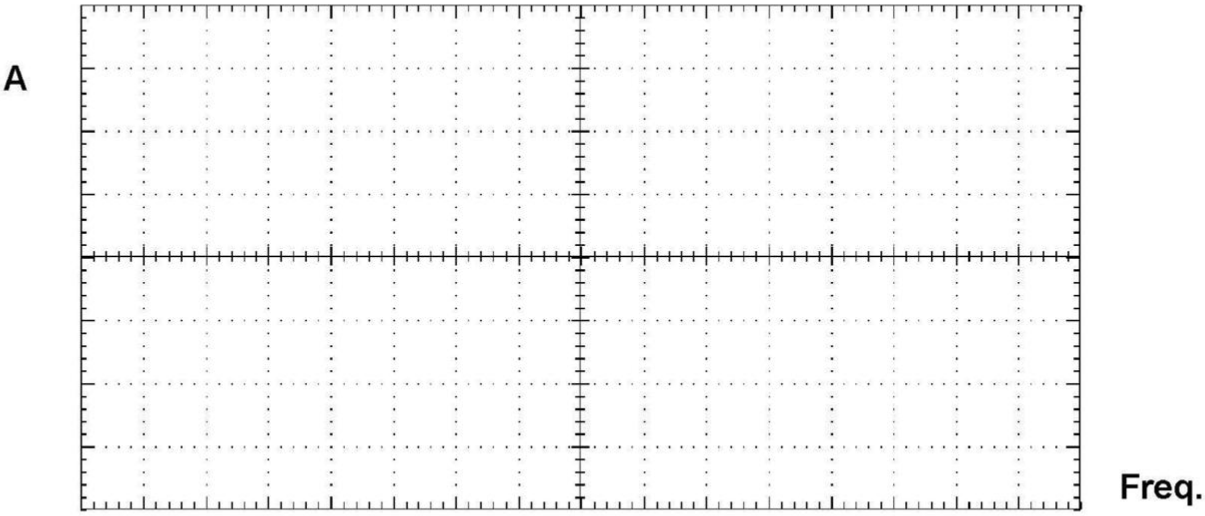
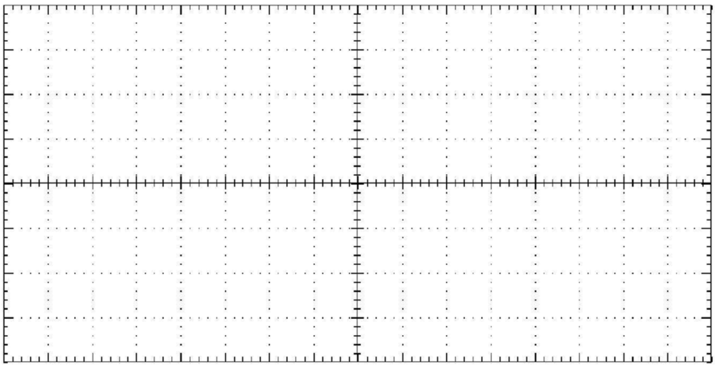
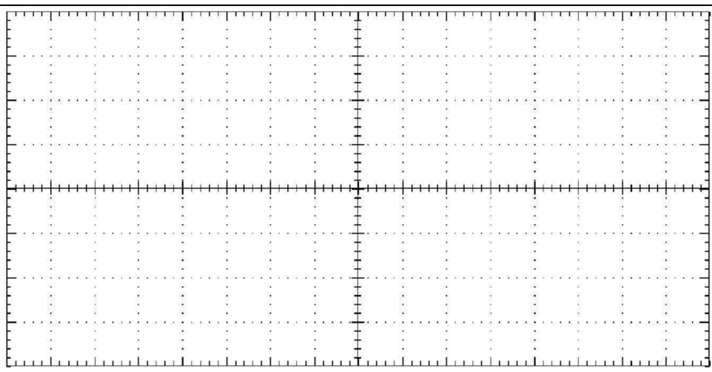


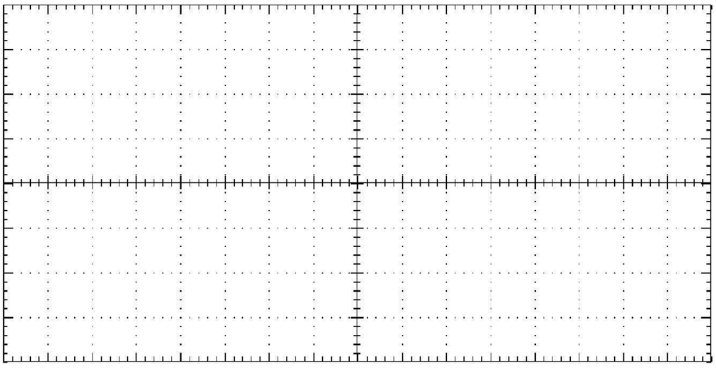
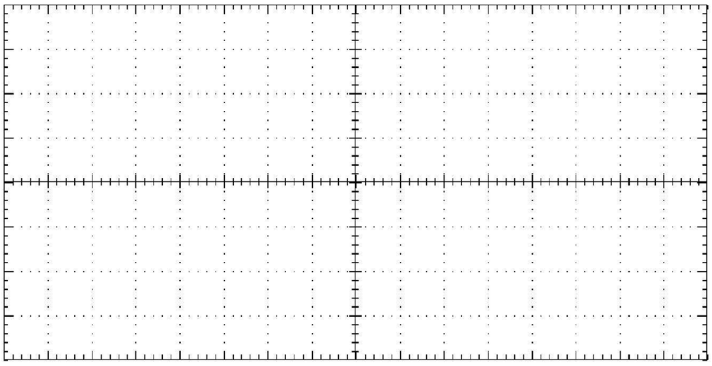
Table 1.8 Simulated ECG Experiment.

** Take the output of the ECG simulator as the standard reference (the ECG simulator is an additional piece of equipment and must be purchased separately).

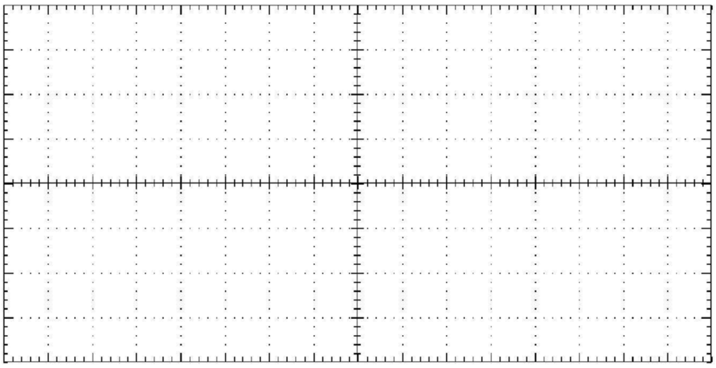
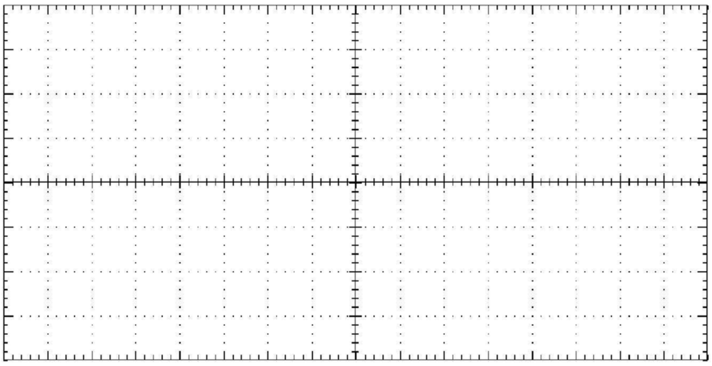
Lead I Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

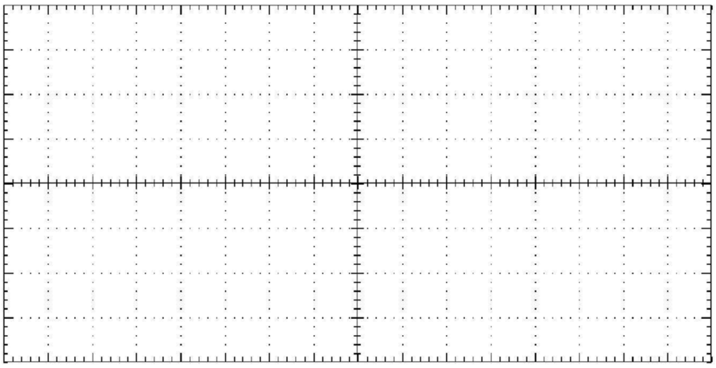
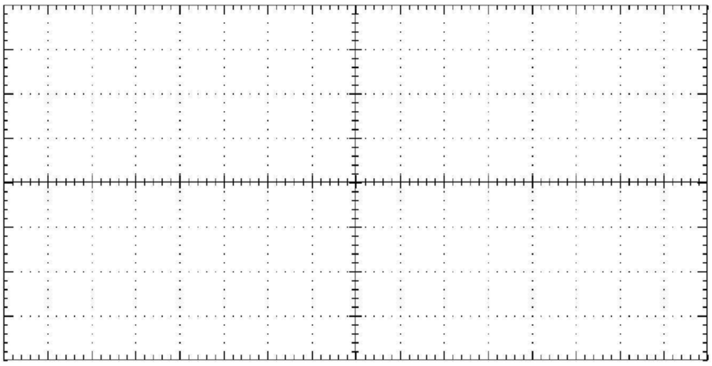
Lead II Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

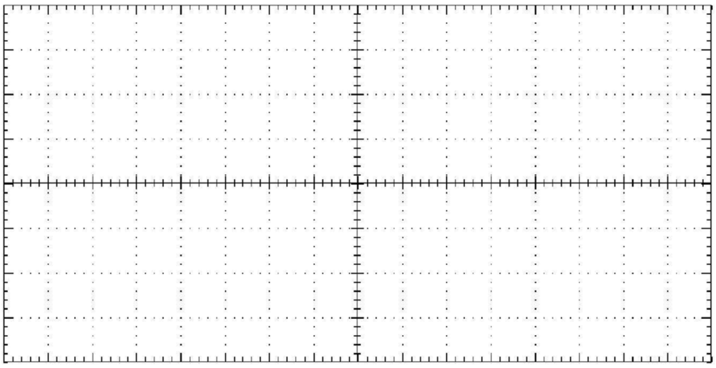
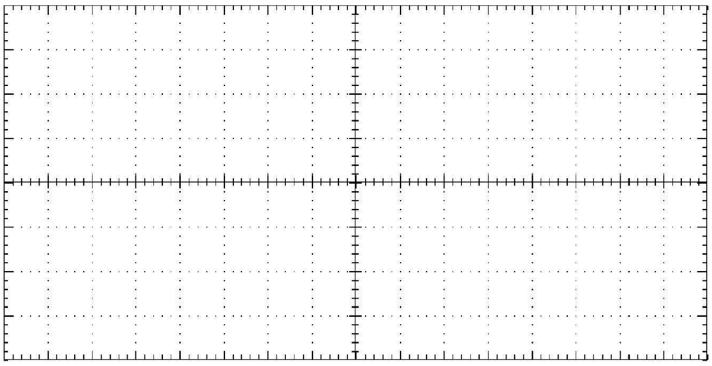
Lead III Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

aVR Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

aVL Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

aVF Output Waveform

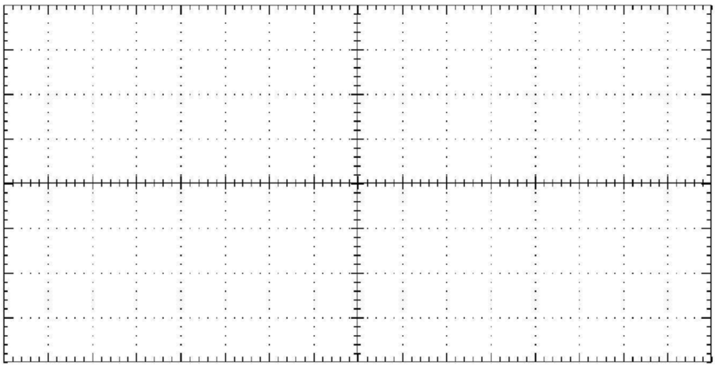
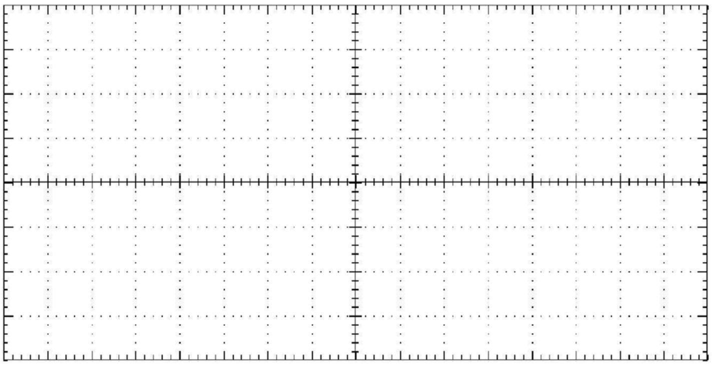
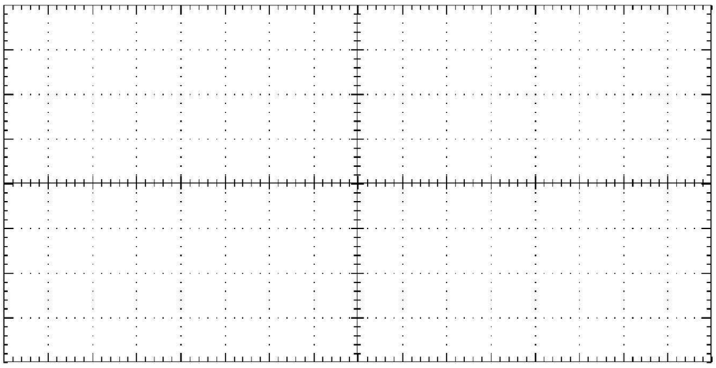
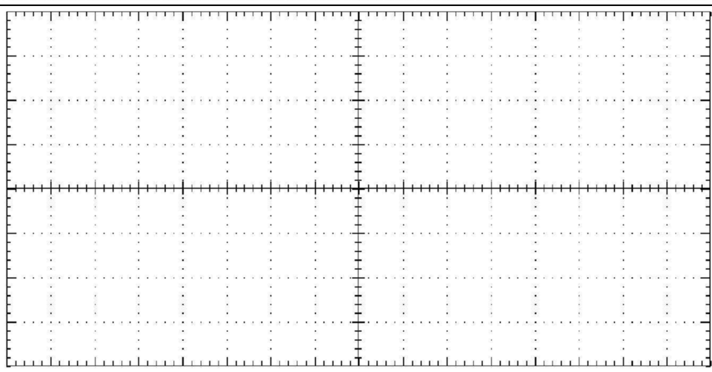
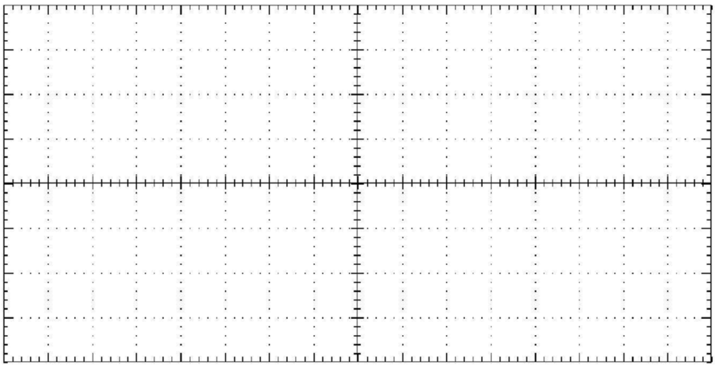
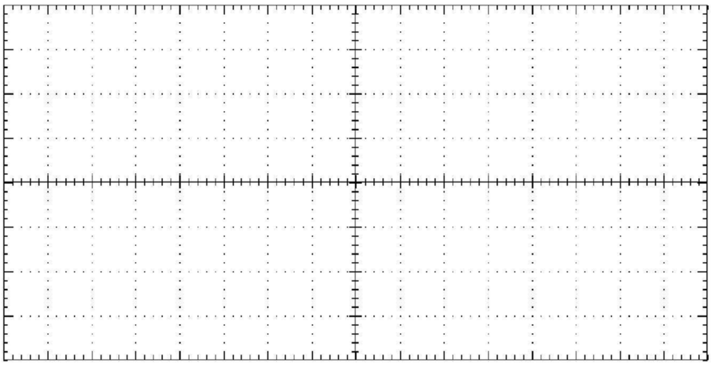
		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

Table 1.9 Real ECG Experiment (** Real Human ECG Experiment)

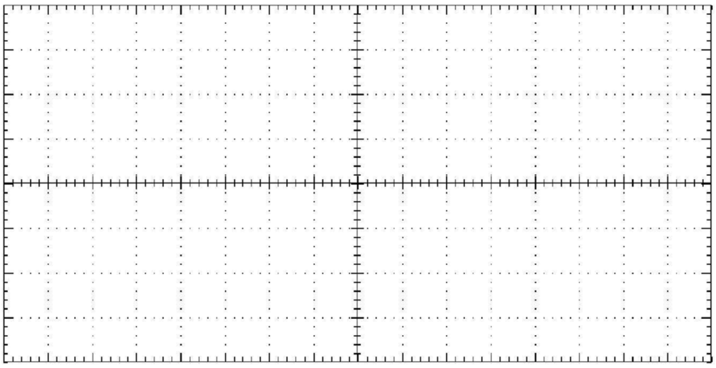
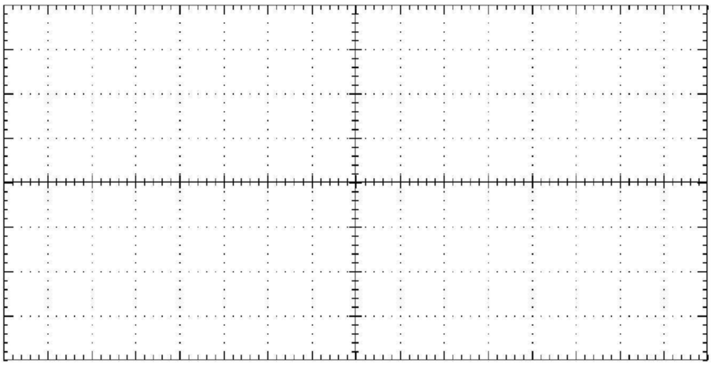
Lead I Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

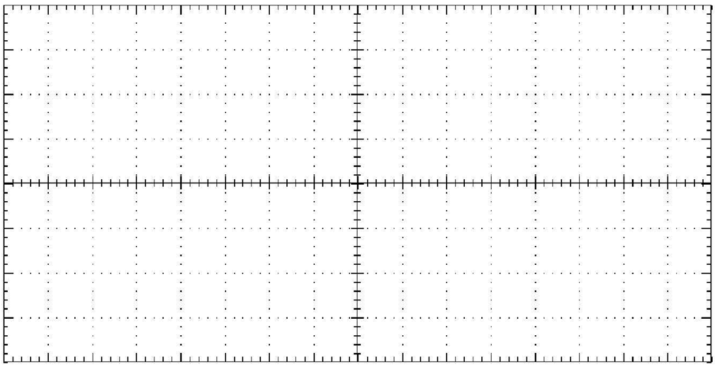
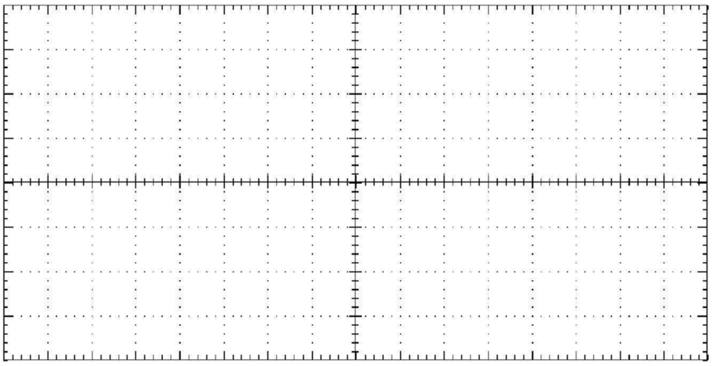
Lead II Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

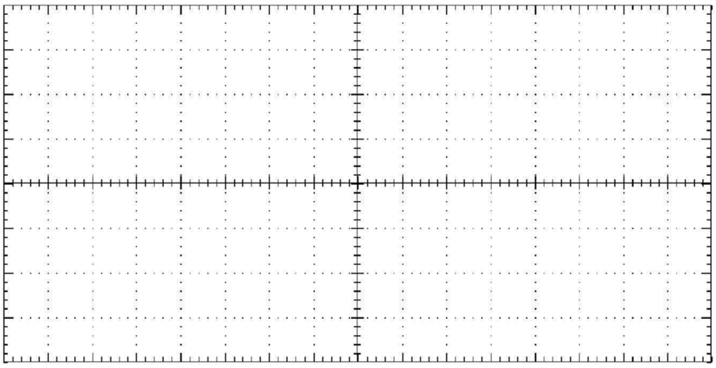
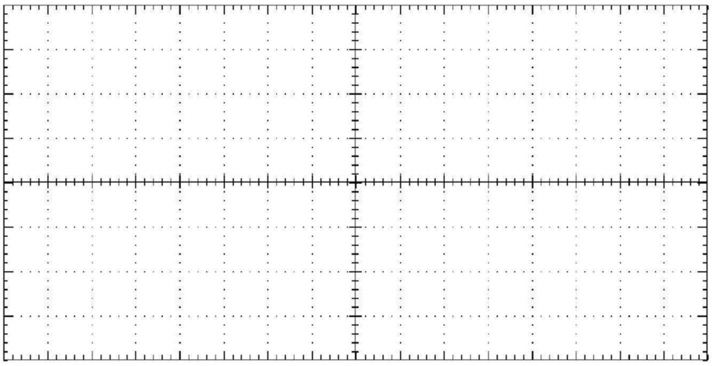
Lead III Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

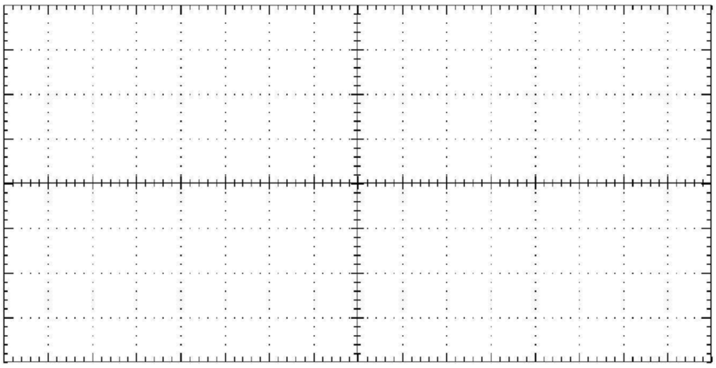
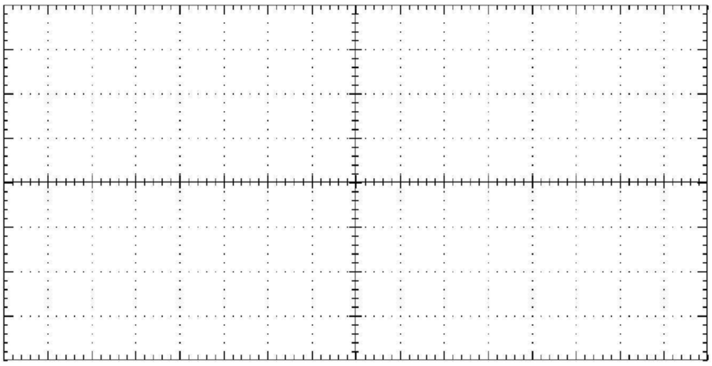
aVR Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

aVL Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

aVF Output Waveform

		Vo1 Output
HPF 1 Hz 5,6	Set the gain setting to medium	
HPF 0.1 Hz 7,8	Set the gain setting to medium.	

1.6 QUESTIONS

1. Where is the -3dB frequency in the high-pass filter experiment?

2. Where is the -3dB frequency in the low-pass filter experiment?

3. What is the bandwidth frequency in the band-stop filter experiment?

4. How does the output signal change when VR2 is changed in the band-stop filter experiment?

5. How does the output signal change when the -3dB frequency of the high-pass filter is changed in the ECG experiment?

6. Explain whether amplifier gain affects the ECG waveform.

7. Explain why the output obtained when an ECG simulator is used as a signal source is better than the result obtained in the human body ECG experiment.

8. What is the difference between DC and AC measurements of the digital oscilloscope in measuring the ECG waveform?